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Matter injection technology for DEMO, state of the art

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HIGHLIGHTS

- Mass losses in matter injection systems are to be considered.
- Pellet injection to the magnetic high field side is essential for core particle fueling.
- Geometry of transfer line is crucial for efficiency.
- Gas Injection System valves are switching between tokamak bypass and vacuum vessel providing continuous flow from Tritium plant and enables fast switching times.

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ABSTRACT

DEMO will be a burning fusion device, most likely a tokamak type and thus, the plasma needs to be re-fuelled. A project was launched in the European DEMO Programme to develop concepts for the matter injection. This approach and the actual status of the project are presented.

In a first step, requirements for actuators on plasma core density were elaborated. Related modelling activities indicated that only sufficiently deep fuel deposition can achieve target operational parameters. Hence, suitable techniques had to be identified and evaluated with respect to their availability and capability. Several techniques for pellet injection have been benchmarked in view of the defined requirements. Finally, cryogenic pellet injection was chosen as the main actuator on plasma core density. From further modelling activities, assuming for the pellet mass the ITER reference value, required launching speeds were derived, with respect to different injection geometries. Gas puffing and the respective technical system are necessary for pre-fill, ramp-up and plasma confinement enhancement. The ITER gas injection system (GIS) is assessed in view of suitability for DEMO. The piping system and the manifold concept can be adopted. The Gas Valve Box (GVB) is considered not to be an optimum solution for DEMO. Instead of this GVB, a pressure based RUN/VENT flow regulation and injection system is proposed in order to meet DEMO requirements. The principle of this system is described as well as some considerations about injection locations; further orienting gas flux numbers are provided.

1. Introduction

The Demonstration Fusion Power Reactor (DEMO) is supposed to be the step in between ITER and the first commercial fusion power plant. In the framework of one mission of the "Work plan for the roadmap to fusion energy 2014–2018" [1] a work package Tritium, Fuelling and Vacuum (TFV) was launched [2]. As part of this project, a fuelling system for DEMO has to be developed. This system must provide the required D-T fuel mixture to maintain the plasma as foreseen by the plasma scenarios. Hence, all investigations and specifications are derived from the demand of the burning plasma. In case of 1.572 GW fusion power in DEMO He will be created by nuclear fusion at a rate of $5.7*10^{20}$ atoms/s. In order to grant the maximum content of 10% He ash, the D/T replenishment flux has to be $1.2*10^{22}$ atoms/s. Depending on the transport situation between the pedestal and the core, the requested particle flux at the SOL could be up to $1.2*10^{23}$ atoms/s. The relation between the hydrogen isotopes deuterium and tritium is still not determined. The overall technological efficiency of material transfer from matter supply to plasma core can be as low as about 0.1.

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Hence, the requested material flux can grow up to $1.2*10^{24}$ atoms/s which illustrates that great care must be taken to design a fuelling system with a sufficiently small mass loss.

The gas injection system (GIS) will supply the material needed for pre-fill, ramp up and plasma enhancement gases. For pre fill, $\sim 2*10^{23}$ DT atoms/s must be puffed in DEMO ($V = 2538\,m^3$). For divertor detachment, the requested gas flow could be in the range of $2.2*10^{22}$ atoms/s. These numbers are estimated values and just for orientation.

2. Core fuelling

2.1. Interface analysis

Matter injection implies the transport of material from the source (gas source) to the vessel/plasma passing interfaces.

Each interface has a potential to cause some loss of material which is then missing on the target location. A thorough analysis of these interfaces and the loss paths was performed and the result is displayed graphically in Fig. 1. The overall efficiency is the product

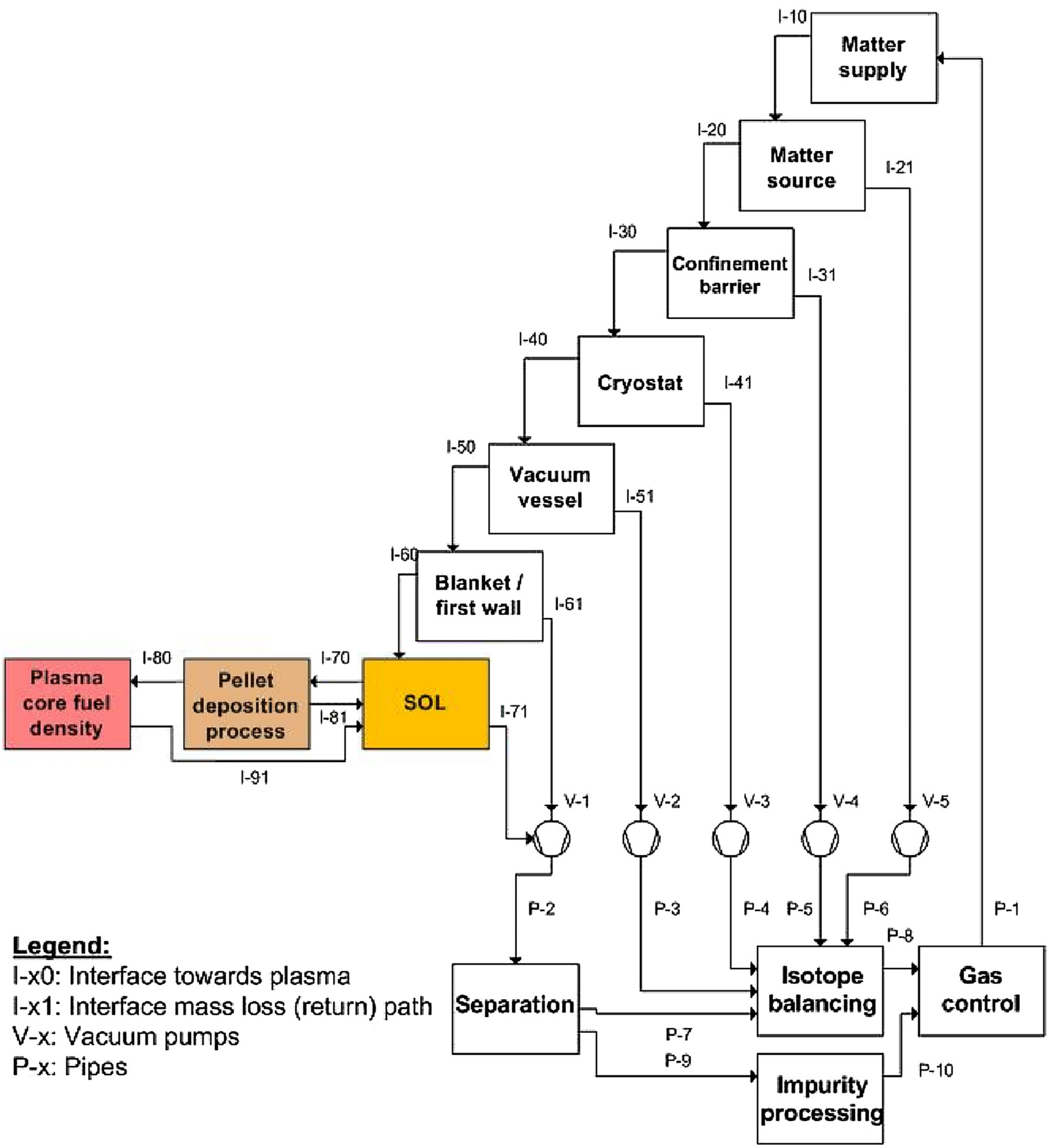

Fig. 1. Interface description with loss paths of the pellet injection part of the fuel cycle as an example. For GIS, interfaces can be described in a similar way. The mass loss on each interface has to be handled by the pumps and the gas handling system. In contrast to the transport processes in the plasma, the efficiency of the fuelling system can be influenced by technology efforts. In particular, this is important for pellet injection with transfer lines. The optimization of the mass losses has a big influence on the overall efficiency and the number of material circulation in the fuelling system.

of the efficiencies of each interface, thus one weak component will strongly affect the result [3].

The pivot of the analysis is the interface "Scrape-off-Layer" (SOL); the material has to pass it on the way to the plasma core while a certain fraction is directly reflected or ejected after a very short time. Between the SOL and the plasma core, complex transport processes supply the fuel to the core and remove the ash and surplus fuel. This flux has to pass the SOL as well.

2.2. Modelling and engineering activities

For actuation on the core density in DEMO, modelling showed gas fuelling to be incapable for reaching the required target. Hence, pellet injection was selected as sole actuator for core density control [4]. A good fuelling efficiency is essential to minimize efforts on the systems, involved in the fuel cycle (e.g. pellet system, vacuum pumps, gas handling system). In addition, DEMO must not exceed the limit for the tritium inventory.

Modelling activities were launched to get specifications for a technical fuelling system. In contrary to present devices, the displacement of the ablated material due to the drift down the magnetic field gradient in DEMO is larger than the penetration during the ablation. This enforced the pellet injection from the magnetically high field side (HFS); low field side injection will have poor performance, even at very high pellet speed [5]. A possible way to access the HFS in DEMO was found in collaboration with the CAD design team. This solution was taken as technical restriction condition for the modelling activities. Pellet injection from the vertically high field side (VHFS) was studied as well. The efficiency of this option suffers from unfavourable relation of the injection to the plasma elongation and the drift. This shortfall can be compensated using high pellet speed (~5–10 km/s) only applicable in direct flight [6].

2.3. Open loop modelling activities

The injection from the vessel inboard (HFS) requires the implementation of a pellet guiding system. This guiding system plays an important role in the overall efficiency of the fuelling system. Its geometry determines the boundary conditions for maximum pellet speed. The mass loss is to be minimized, considering adequate efficiency passing the SOL.

Open loop modelling activities (without feedback from the plasma) were performed to investigate the influence of different injection geometries on the fuelling efficiency of the plasma. Three design options were elaborated along different optimization directions, namely (1) the component of pellet speed perpendicular to the magnetic surface v_R, (2) the absolute pellet speed and (3) the penetration angle of the pellet in the plasma. For the optimized injection geometries achieved fuelling efficiencies are $\varepsilon > 0.97$. This value corresponds to the ratio of the flux passing I-80 to the flux passing I-70 in Fig. 1 disregarding the processes between the SOL and the separatrix. It takes only into account the effect of the drift induced by the inhomogeneous magnetic field and is likely to be an upper bound [5]. Fig. 2 illustrates the according geometries.

The maximum pellet speed indicated in Fig. 2 is estimated through the empiric AUG scaling $v_p\left[m/s\right] = 36.4\sqrt{R_c/\Phi_p}$, where R_c is the curvature radius and Φ_p the pellet size. Due to the weak dependence of the fuelling efficiency of the injection location within the investigated area, the main criteria will be the mass loss due to erosion of pellet in the transfer lines. The mass loss is mainly dependent on the stress on the pellet connected to bending radii of transfer system and pellet speed. All activities were made under prerequisite, that the radius of curvature does not change the

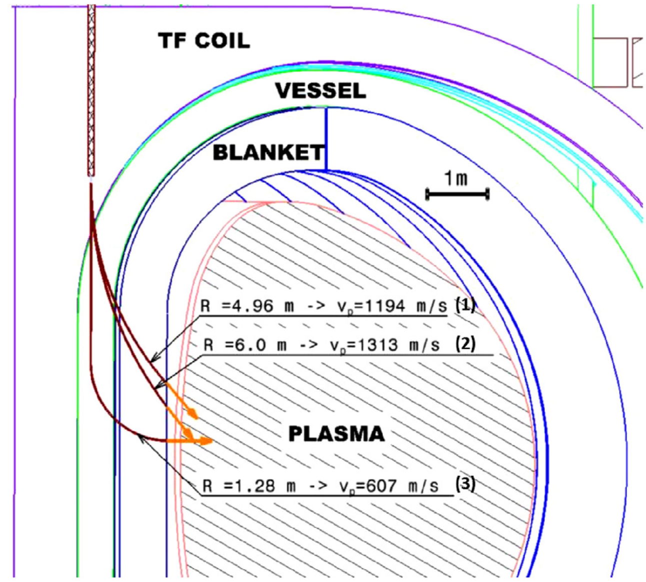

Fig. 2. Geometry of injection lines optimized for (1) the component of pellet speed perpendicular to the magnetic surface v_R, (2) the pellet speed and (3) the penetration angle of the pellet in the plasma.

direction. "Roller coaster like" transfer systems are inappropriate for a reactor fuelling system.

The next step, closed loop modelling activities (including feedback from the plasma) is on hold, as the actual valid plasma scenario for DEMO is subject to revisions. These activities will be relaunched as soon as the new scenario will be available.

Doing this, attention must be paid to the speed dependence of the mass loss in the transfer line. This has to be integrated in the optimization process.

3. Gas injection for pre-fill, ramp up and plasma enhancement

The Gas Injection System (GIS) will not be suitable for core particle fuelling, the bigger part of the particle flow will be reflected on the plasma edge. Nevertheless such a system will be needed for pre- fill, ramp up and injection of plasma enhancement gases. The GIS is together with the pellet injection system incorporated in the fuel cycle and embedded in the hydrogen isotope handling system.

3.1. Gas injection system

The requirements for the GIS are to be derived from the demand for pre-fill, ramp up and supply of plasma enhancement gases. These requirements are not yet settled for DEMO and were until now not yet included in the scope of the project TFV.

Generally speaking, the GIS shall be able to provide a precise mass flow, which is fast switchable and adjustable. This will be a strong demand, the measurement and control of the flux has to be insensitive to the environmental conditions of a Tokamak. The plasma control will require short time constants.

The GIS shall withstand the (changing) magnetic field, the neutron flux and thermal issues without showing enhanced wear or drift.

The access to components in fusion devices is often hampered by complex structures or isolating vacuum. The selected system shall be easy to maintain. Due to the long timescale of the project, the adaption to new technology should be possible.

The ITER solution [7], using Gas Valve Boxes with thermal mass flow controllers and one single injection line is regarded not to be

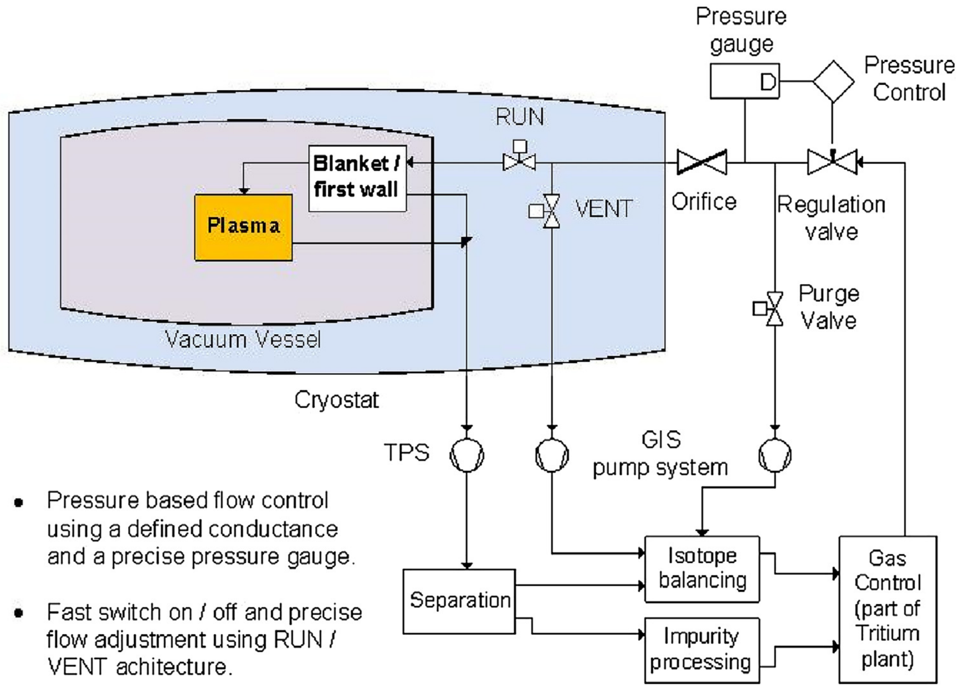

Fig. 3. Schematic view of pressure based gas flow control system with RUN/VENT valve and related pumping and gas processing system.

the optimum solution for DEMO. The response time for the application of plasma enhancement gases is regarded to be too long and the present layout hampers the option to inject several gases simultaneously.

3.2. Gas flow control

Each kind of gas needs its own injection system; the change of gas is intended only for maintenance (e.g. purging).

The flow control will be done via a pressure based control system. The control parameter is the pressure in front of an (adjustable) orifice which is proportional to the gas flow within the working range (choked flow condition). The pressure is a direct measure and more precise than flow meters based on thermal effects in a Tokamak environment characterized by strong electromagnetic perturbations. The flow control unit can be placed far away from the coils; the gas flow after the orifice is feed by a tube closed to the torus. A RUN/VENT valve switches the flow either directly in the pumping line or towards the torus. A tube after this valve feeds the gas through the vacuum vessel wall and the breeding blanket. This tube is short, thus the time constant for switching ON/OFF is short. The RUN/VENT valve block can be designed rough enough to be placed closed to the torus. Also for set point changings, this setup will be able to provide good performance.

Above all, continuous flow is easier to process in a closed loop gas supply system than a flow with strong fluctuations. The VENT line can be regarded as "Tokamak bypass", as illustrated in Fig. 3.

During further investigations, the dimensioning of components to optimize the performance must be elaborated. The main parameters are the diameters of the orifice and the tubes of supply, injection and vent lines as well as the conductance of the RUN/VENT valve. The pumping power of the VENT line must be settled. At the present stage, this is not yet possible, as the requirements for the pre-fill, ramp up and plasma enhancement gases are still unknown.

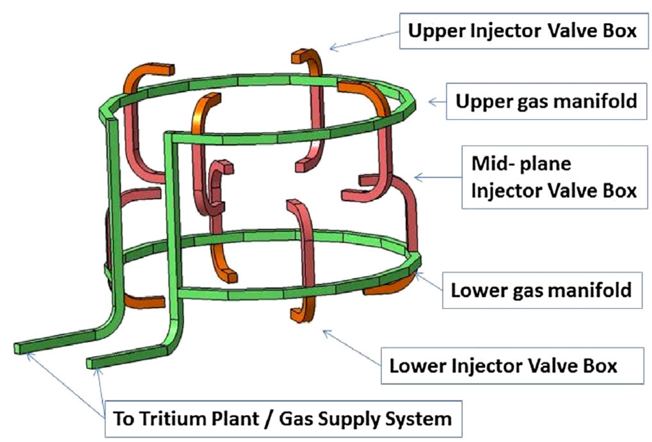

Fig. 4. Gas Manifold providing the option to supply 4 lower and upper injectors and up to 8 mid plane ones.

3.3. Gas manifold

The piping network (manifold) connects the injection locations and the tritium plant using a tubing system. The tubing system worked out for ITER [8] is regarded to be suitable for this purpose as well. It consists of a pipe bundle of 6 tubes attached on the evacuation tube. This pipe bundle is covered by an envelope with an outer diameter of 237.1 mm, made from two half shells.

The number and position of injection location is still unknown. Figs. 5 and 6 illustrate two different possible solutions of location of gas injection points. This status will last until the plasma scenario will be stated; determining the number and kind of gases, their purpose and the subsequent flow quantities. Thus a preliminary design has to be worked out, allowing flexible adaption to the final requirements. As for ITER, two rings of manifolds are proposed, one in the upper half and one in the lower half of the torus. Possible requested mid plane injection locations can be supplied from either the upper or the lower level manifold, see Fig. 4.

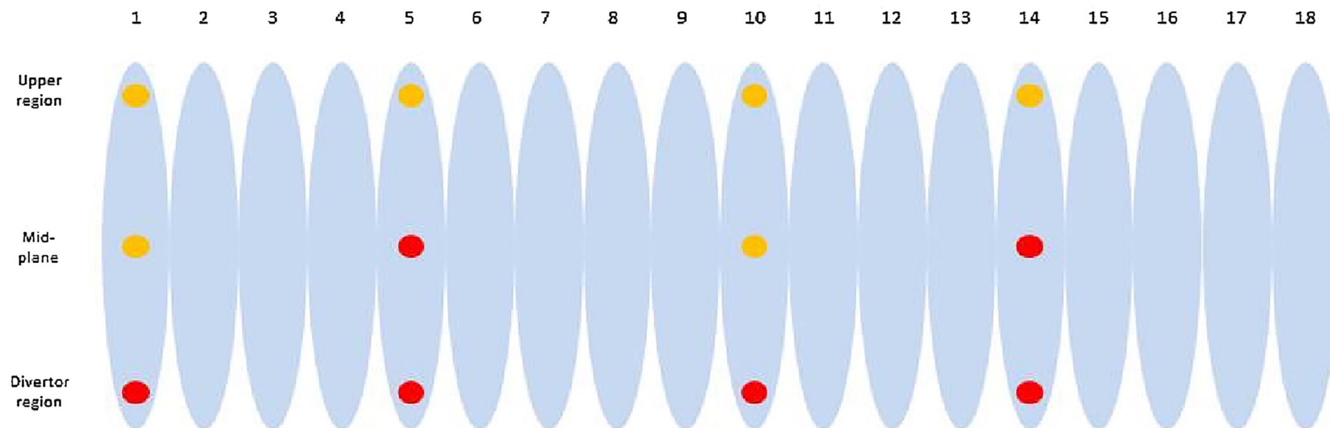

Fig. 5. Option 1: 3 poloidal and 4 toroidal locations, upper and lower manifold in the same sector: total 12 locations. The red locations are supplied by the lower manifold, the yellow ones by the upper manifold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

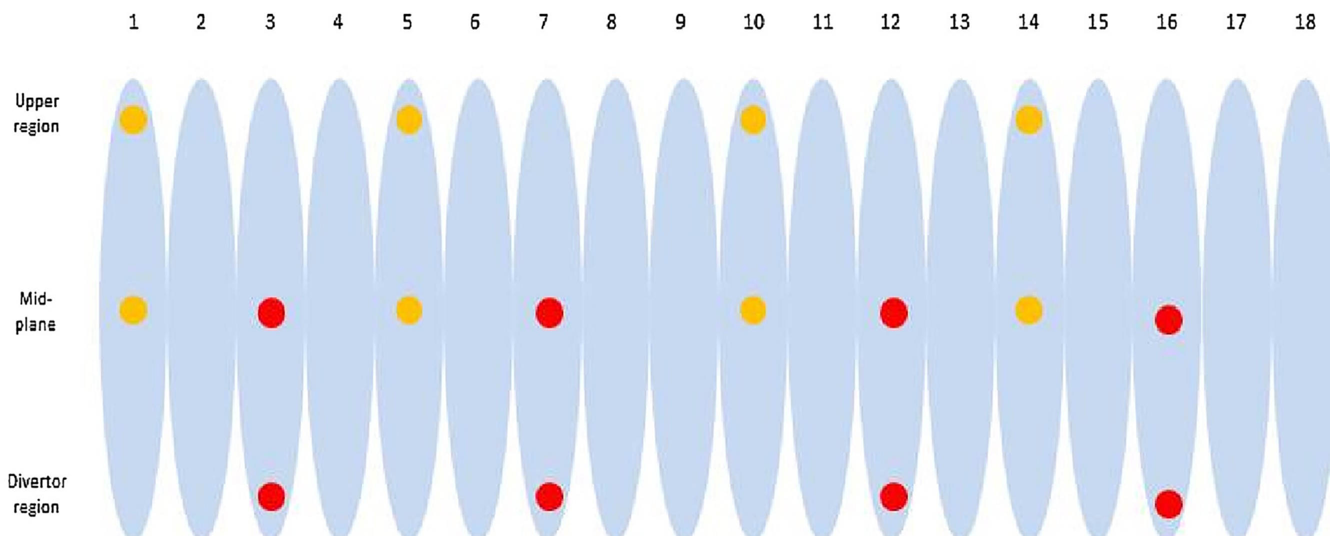

Fig. 6. Option 2: 3 poloidal and 4 toroidal locations, upper and lower manifold in alternated sectors: total 16 locations. The red locations are supplied by the lower manifold, the yellow ones by the upper manifold. This version provides more injection locations with a possibly more uniform gas distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

On the contrary to the ITER system, the continuous flow in the gas line is switched from the return line (VENT) to the injection port (RUN) and vice versa. Thus, an additional similar tubing system has to be installed for the return lines; which conducts the flow back to the gas supply system. Thus the piping network will be more complex. It seems to be advantageous, to use two bundles of 7 tubes instead of one with 13. The vacuum line would be required once only.

4. Conclusion and outlook

This contribution reports achieved results and the actual status of the matter injection project in TVF. The goal is to establish a conceptual design of Matter Injection System for DEMO using all information, founded during exploration the solutions for ITER, state of the art of technology and taking into account the findings of plasma physics research. The basic principle underlying our activities is the integral view on the matter injection system. All consideration starts at the plasma requirements and do not stop until the very beginning of the technical processes. This leads to the following results:

- All material, needed for the fusion process has to pass some interfaces with the potential of accumulated loss of material (with regard to the process). This is obvious for cryogenic material (evaporation), but do not only exist there. The gas flow in the VENT lines must be regarded as mass loss, even presumably sound manageable. These mass losses must be minimized; they burden the gas handling system and are counting to the T- inventory.
- The fuel injection has to be done with pellets from the magnetic high field side using a transfer system. Gas puffing is not suitable. The modelling activities are showing an operation window with reasonable fuelling efficiency assuming technical reasonable boundary conditions concerning the transfer system.
- The closed loop activities (including the feedback from the plasma) are on hold until a new relevant integrated DEMO plasma scenario will be available including plasma performance enhancement, radiative power exhaust and divertor buffering.
- Albeit the Gas Injection System is not useful for fuelling it will be needed for pre-fill, ramp up and supply of plasma enhancement gases. The latter could be injected via pellets in some cases as well. The gas injection for DEMO must be developed further from the ITER GIS. A pressure based flow control using RUN/VENT valves

ensures fast response time. This causes continuous flow through the gas handling system, which is regarded to be favourable. Each kind of gas will use its own injection tube, thus the system will be able to serve requirements from the plasma scenario concerning e.g. core radiation and divertor detachment. These requirements are not yet known.

The project will continue resulting in a conceptual design for the Gas Injection System. As soon as the new DEMO plasma scenario is settled, the closed loop modelling activities will be relaunched. Based on the results of these activities, a conceptual design for the pellet injection system will be worked out.

Any fuelling system must penetrate the breeding blanket/first wall. First coordination talks were started to identify the conflict of goals between the two systems. Finally a sound solution must be found in order to enable good performance of DEMO.

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